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CONTENTS

Page

Association Notes 199*r*

Control of Cracking in the Metal Arc Welding of High Tensile Structural Steels 201*r*

ASSOCIATION NOTES

Sixth Annual General Meeting

The Sixth Annual General Meeting of the Association was held at the Research Station, Abington, near Cambridge, on Wednesday, 25th July, 1951, when the Report of the Council, Statement of Accounts for year to 31st March, 1951, and Balance Sheet at 31st March, 1951, were received and adopted.

Sir Charles Lillicrap as Chairman of the Council introduced the report of the Association for the year. He was pleased to report a very satisfactory year's work by the various Research Committees and a continued increase in membership. It was becoming increasingly evident that those in industry interested in welding were taking full advantage of the resources and accumulated knowledge of the B.W.R.A. Recently a Summer School had been organised at Ashorne Hill and so successful was this venture that tentative plans were being made for a similar course to be held next year. The Liaison staff backed by the investigators had been receiving more calls than heretofore for advice from members and non-members, and translating highly technical data into workshop practice. This important task of bridging the gap between the research laboratory and workshop served a basic object of the Association.

On the financial side, the Council, bearing in mind the capital commitments involved in purchasing plant and building a laboratory, had transferred to reserves the sum of £2,400. The Council considered it imperative for the Association to have adequate facilities for carrying out its

researches effectively and was encouraged by the response of Members who had contributed towards the cost. The Chairman was gratified to learn that as a result of his appeal letter of April last that over £2,000 had been received and this money would help provide for the testing plant so necessary for the research programme. During the year the Association was honoured by the choice of the Director as the leader of the Specialist Team on Welding which visited the U.S.A. under the auspices of the Anglo-American Council.

Finally, the Chairman paid tribute to his colleagues on the Council, and members of the Research Board, Finance Committee and Technical Committees whose advice and interest was always appreciated by the staff. The Council also wished to report its appreciation of a satisfactory year's work completed by the Director and his staff.

Research Report on "Control of Cracking in the Metal Arc Welding of High Tensile Structural Steels"

Several advantages are to be gained from the use of low alloy steel in the building of bridges and similar structures The increased tensile strength of such steel results in a considerable saving in weight of the integral parts of the structure, with a consequent economy in transport and erection.

The welding of higher tensile steels, however, is accompanied by a type of failure which is known as hard zone cracking. The problem of welding these steels satisfactorily, without cracking, is one which interested the Ministry of Supply. Accordingly, the Association undertook an investigation into this problem, the work falling under the guidance of the FM.8 Committee.

A typical structural unit was fabricated from a selected steel. Cooling rates were measured in the heat affected zone adjacent to each weld. All the welds were subsequently sectioned and examined microscopically for cracks. In this way cooling rate was related to the occurrence and extent of cracking.

It was found that a critical cooling rate existed for each type of electrode when used to weld the given steel. When this critical cooling rate was exceeded, hard zone cracking occurred.

This paper, which was first presented to the International Welding Congress in July, describes the investigation and the results obtained. The results are used to show how cracking can be avoided by making welds of a minimum fillet size without the use of preheat.

Mention is also made of a new weldability test which can be made on plates of various thicknesses to give different grades of severity. This test, called the Controlled Thermal Severity (C.T.S.) test, can be used to assess the weldability of a steel, to determine the suitability of an electrode, or to simulate conditions in a given structural joint.

The members of the FM.8 Committee, under whose guidance the work was carried out, are as follows:

Dr. L. Reeve (*Chairman*) ..	Appleby Frodingham Steel Co. Ltd.
Sir Donald Bailey	Ministry of Supply.
W. Barr	Colvilles Ltd.
J. Dearden ..	British Railways
Dr. H. Harriss ..	Babcock & Wilcox Ltd.
F. A. Ball	Mond Nickel Co. Ltd.
G. L. Hopkin ..	Ministry of Supply.
C. E. Sherwin ..	Admiralty.
Dr. E. C. Rollason	Murex Welding Processes Ltd.
H. F. Tremlett ..	United Steel Companies Ltd.

Technical Secretary : L. W. Kastell

ASHORNE HILL SUMMER SCHOOL, 1952

Dates to Remember

In view of the success achieved at the Ashorne Hill Summer School held in May and June this year, the Association has decided to hold another school next year at the same place from :—

Wednesday, 16th July, until Friday, 25th July.

The School will, on this occasion, be divided into two parts—the first part from Wednesday, 16th July, till Sunday, 20th July, being for those concerned with the purely practical aspects of welding, and the second part from Sunday, 20th July, till Friday, 25th July, being for those concerned with design, inspection and manufacturing problems. Further details will be issued later.

CONTROL OF CRACKING IN ARC WELDING HIGH TENSILE STRUCTURAL STEELS

This paper is the result of an investigation undertaken by the British Welding Research Association for the Ministry of Supply, and is reproduced by permission of The Controller, H.M. Stationery Office. (Crown copyright reserved).

By C. L. M. COTTRELL, M.Sc., M. D. JACKSON, B.Met., A.I.M.
and J. G. WHITMAN, M.Eng., Ph.D., A.M.I.C.E.

Introduction

The investigation described in this paper concerns the problem of welding a prefabricated bridging structure in a high tensile structural steel. It was most desirable to use high tensile steel for this purpose as there would be considerable saving in weight of the integral parts with consequent economy in transport and erection.

The control necessary in this fabrication concerns the elimination of a particular form of cracking which is peculiar to welded high tensile steels. This type of crack occurs in the hard zone of the parent metal, bordering on the weld, which has been affected by the welding heat and is mainly martensitic in high tensile steels on account of the alloying elements present.

There are, of course, other forms of crack which may occur in the weld metal itself and these are just as important from the Engineer's point of view. The risks of such cracking, however, are very little more in this case than when mild steel is welded so that their control, which lies in sound welding practice, is not special to the high tensile structural steels.

Weld boundary cracking, or hard zone cracking, has therefore been taken as the criterion of weldability, throughout this work.

This paper describes how the structure was fabricated from low alloy high tensile steel rolled sections and plates using the A.C. metallic arc process. All the relevant data were recorded for each joint. The joints were afterwards sectioned and examined for the presence or absence of cracks, and in this way it has been possible to arrive at the minimum requirements to ensure crack free welds.

The steel used may be regarded as typical of the modern high tensile structural steels and has a 0·3 per cent. proof stress of 27 tons/sq. in. and an ultimate stress of 45 tons/sq. in. in the lighter sections. A range of twelve different joints was examined in this way and, though the size of these members was small compared with the more usual bridge components, the results of the investigation have shown that the greatest severity of welding conditions has been obtained. For this reason the results can be applied to the heavier joints more commonly found in bridging work.

Earlier work had shown that the controlling factor in the formation of hard zone cracks is the rate at which the weld cools. Shrinkage stresses would not of themselves produce this type of crack and would only function in opening out a crack when this had been formed by too high a rate of cooling. Cracks of this nature have been produced in free welds with no restriction, and severe restraint was found to give no cracking when the rate of cooling was below a certain figure depending on the electrode used. This type of crack does not appear on the surface of the weld, is extremely small in width but not necessarily in area, and, unfortunately, cannot be detected except with the aid of the microscope after sectioning the weld and carefully polishing and etching. For this reason these cracks are known as micro-cracks and in this work were examined with a magnification of 400.

The extent to which these cracks spread has been shown to bear a relationship to the rate of cooling so that the proportion of weld cracked can be used as an indication of the severity of the conditions.

Micro-cracks may not appreciably affect the static strength of a welded joint but, nevertheless, their presence is undesirable because they are likely to impair the fatigue strength of a structure and, in addition, shrinkage stresses may open out the cracks to a dangerous extent. Welding conditions resulting in such cracks represent the border line conditions between no cracking and complete cracking.

For these reasons the welds of the test structure were made with a representative selection of electrodes under carefully controlled conditions, and cooling rates of the heat affected zone were measured in each case.

From the micro examination of the welds it was possible to establish critical cooling rates above which cracking would occur for each of the three types of electrode used, and from the cooling rate measurements a relation was established between energy input, or fillet weld size, and the rate of cooling for each joint (Thermal Severity Curves). It was therefore possible from these results to specify a minimum size of weld deposit to prevent cracking in each of the joints examined.

A new weldability test has been developed with a range of known thermal severities so that the scope of this work can be extended to cover new electrodes or new steels or any combination of the two.

In structural work, therefore, the control of cracking in welding high tensile steels would depend on the use of specific electrodes with minimum deposits to be laid down in one run. This is, of course, a matter for design as well as inspection because the weld sizes are specified on the drawing board and these should not be less than the minimum for each type of joint and electrode to be used.

The effects of pre-heat and post-heat have not so far been studied and, in this work, all welds were made with the structure initially at room temperature. This represents the worst condition in shop welding, because the heat from previous welds would undoubtedly have a beneficial effect in lowering the cooling rates. This fact can be used to help critical welds by arranging the welding sequence at a joint so that earlier welds give a preheating effect. It is hoped to carry out further work on this aspect of the problem and on the effects of initial and final temperatures on the weldability of these steels.

Materials

The " Ducol W27 " steel used in this investigation was supplied by Colvilles Ltd., and was within the composition range given in Table I.

Some of the welds were made between " Ducol W27 " steel and a mild steel. Where this was done, the thermocouples for determining cooling rates were inserted in the alloy steel section. The electrodes used for making the test welds were of the type indicated in Table II according to the B.E.A.M.A./I.O.W. classification and are referred to as " A," " B," and " C " throughout this paper.

Test Procedure and Results

The procedure adopted for making and examining the welds, and for measuring cooling rates is described in detail in Appendix I. The Appendix also contains thermal severity curves for all the joints tested, typical cooling curves, and Table III which summarises the welding conditions used and the results obtained.

Hard Zone Cracking and Rate of Cooling

Reference has been made to the type of failure which may occur in welded alloy steel joints and is known as hard zone cracking. A probable mechanism of this cracking, involving hydrogen, has been suggested by Hopkin[1], and may be explained briefly as follows.

Molecular hydrogen is dissociated in the vicinity of the arc, the source of this hydrogen being mainly water and hydrogen-containing substances in the electrode coating. The atomic hydrogen which is produced enters the metal in the arc and so goes into solution in the molten pool. This is rapidly quenched, not allowing time for the hydrogen to escape, and resulting in a supersaturated solution. The entrapped hydrogen diffuses through the metal during cooling, and continues to do so after room temperature has been reached. Bubbles of hydrogen can be observed leaving the weld metal when a freshly made weld is placed in paraffin after water quenching.

The solubility of hydrogen in steel falls as the temperature is reduced, decreasing suddenly when the austenite transforms. This transformation nearly always takes place at a higher temperature in the weld metal than in the parent plate. For this reason the hydrogen tends to diffuse under pressure into the heat-affected zone of the parent plate.

Rapid rates of cooling associated with arc welding produce a quench effect in the heat-affected zone, which in the case of low alloy steels may give a hard and brittle structure. Such a structure is prone to the initiation of cracks, which may result from stress centres caused by the release of molecular hydrogen at the austenite to martensite transformation of the plate material.

The rate of cooling of the weld zone is controlled chiefly by two factors, the heat input and the heat loss. The heat input is proportional to the size of fillet made, being greater where larger fillets are laid. The heat loss is dependent on the geometry of the joint, heavier sections offering larger paths for heat flow and providing a greater heat sink. Therefore the rate of cooling in a joint between thick sections will be more rapid than in thin sections where the same values of energy input are used, and the joint is said to be more severe thermally. A rapid cooling rate can be avoided by laying a large enough fillet, and this work shows how the minimum fillet size necessary to eliminate hard zone cracking may be derived.

Critical Cooling Rates for Various Electrodes

Other work[2, 3] has shown that the best correlation between cracking and cooling rate is obtained at 300°C. This finding is confirmed by the construction of square root cooling rate curves as shown in Figs. 1, 2, 3, 5 and 6. In these curves the square root of the cooling rate has been plotted against the temperature of the point at which the cooling rate is measured. The square root of the cooling rate has been used, since, for an infinite heat sink a linear relationship is obtained with temperature. The derivation of this relationship has been described in a paper by Rosenthal[4] and the method of plotting has been used here even though the conditions for an infinite heat sink are not obtained in the majority of the joints tested. Where a number of these curves for one particular type of electrode is plotted, it is observed that a critical cooling rate exists, above which cracking is likely to occur. The incidence of cracking may not depend entirely on the rate of cooling at any one temperature, but the rate at 300°C. gives an indication of cooling rates over the whole temperature range, and the temperature selected probably has some significance. The rate of cooling at higher temperatures (500–900°C.) will decide the nature of the structure produced in the heat affected zone, and the rate of cooling at lower temperatures (below 200°C.) probably controls the progress of delayed trans-

TABLE I
STEEL COMPOSITION RANGE

C%	Si%	S%	P%	Mn%	Ni%	Cr%	Mo%	Cu%
0·17 to 0·22	0·08 to 0·23	0·016 to 0·031	0·015 to 0·024	1·24 to 1·49	0·33 to 0·55	0·07 to 0·20	0·25 to 0·27	0·0 to 0·17

TABLE II
ELECTRODES USED FOR THE TEST WELDS

Electrode Type	B.E.A.M.A. Classification	Reference letter
Rutile	E 217	"A"
Rutile—basic	E 317	"B"
Lime (low hydrogen) ..	E 645	"C"

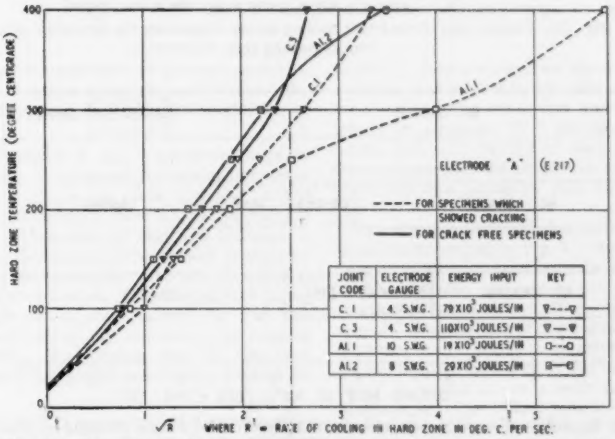

HARD ZONE TEMPERATURE (DEGREE CENTIGRADE)
400
300
200
100
0
C3
A1.2
C1
A1.1
ELECTRODE "A" (E 217)
FOR SPECIMENS WHICH SHOWED CRACKING
FOR CRACK FREE SPECIMENS
JOINT CODE | ELECTRODE GAUGE | ENERGY INPUT | KEY
C. 1 | 4 S.W.G. | 79 X10³ JOULES/IN
C. 3 | 4 S.W.G. | 110X10³ JOULES/IN
A1. 1 | 10 S.W.G. | 19 X10³ JOULES/IN
A1.2 | 8 S.W.G. | 29 X10³ JOULES/IN
1 2 3 4 5
√R
WHERE R = RATE OF COOLING IN HARD ZONE IN DEG. C. PER SEC.

Fig. 1.—Comparison of root rate cooling curves illustrating the derivation of a critical cooling rate. *Electrode A*

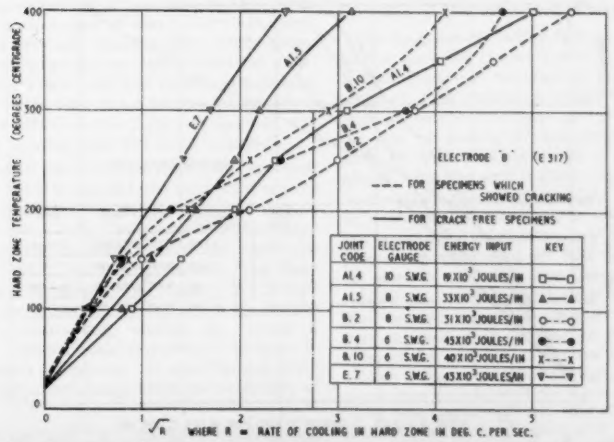

HARD ZONE TEMPERATURE (DEGREES CENTIGRADE)
400
300
200
100
0
A1.5
B.10
A1.4
E.7
B.4
B.2
ELECTRODE "B" (E 317)
FOR SPECIMENS WHICH SHOWED CRACKING
FOR CRACK FREE SPECIMENS
JOINT CODE | ELECTRODE GAUGE | ENERGY INPUT | KEY
A1.4 | 10 S.W.G. | 19 X10³ JOULES/IN
A1.5 | 8 S.W.G. | 33X10³ JOULES/IN
B. 2 | 8 S.W.G. | 31 X10³ JOULES/IN
B. 4 | 6 S.W.G. | 45X10³ JOULES/IN
B. 10 | 6 S.W.G. | 40 X10³ JOULES/IN
E. 7 | 6 S.W.G. | 45 X10³ JOULES/IN
1 2 3 4 5
√R
WHERE R = RATE OF COOLING IN HARD ZONE IN DEG. C. PER SEC.

Fig. 2.—Comparison of root rate cooling curves illustrating the derivation of a critical cooling rate. *Electrode B*

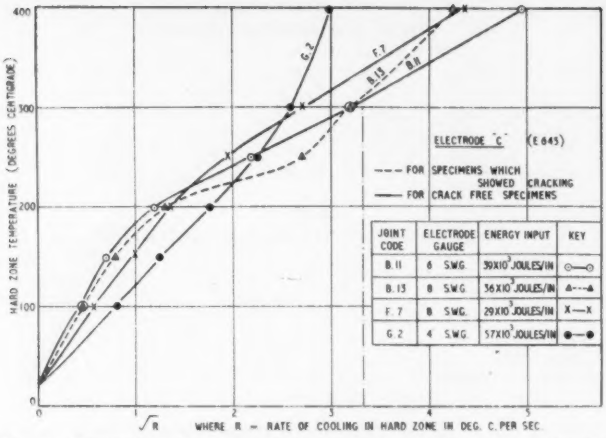

HARD ZONE TEMPERATURE (DEGREES CENTIGRADE)
400
300
200
100
0
G.2
F.7
B.13
B.11
ELECTRODE "C" (E 645)
---- FOR SPECIMENS WHICH SHOWED CRACKING
—— FOR CRACK FREE SPECIMENS
JOINT CODE | ELECTRODE GAUGE | ENERGY INPUT | KEY
B.11 | 6 S.W.G. | 39X10³ JOULES/IN
B.13 | 8 S.W.G. | 36X10³ JOULES/IN
F.7 | 8 S.W.G. | 29X10³ JOULES/IN
G.2 | 4 S.W.G. | 57X10³ JOULES/IN
0 1 2 3 4 5
√R
WHERE R = RATE OF COOLING IN HARD ZONE IN DEG. C. PER SEC.

Fig. 3.—Comparison of root rate cooling curves illustrating the derivation of a critical cooling rate. *Electrode C*

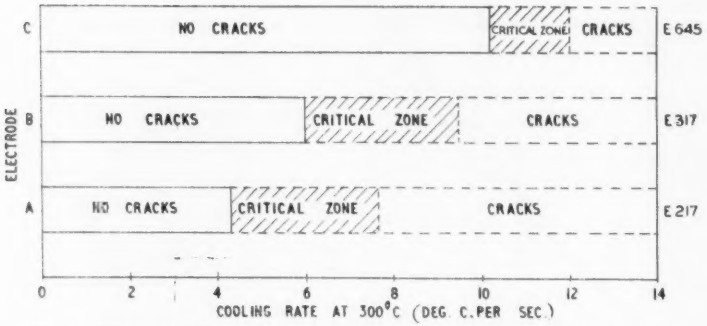


Fig. 4.—Effect of cooling rate and electrode type on hard zone cracking in Ducol W.27 steel.

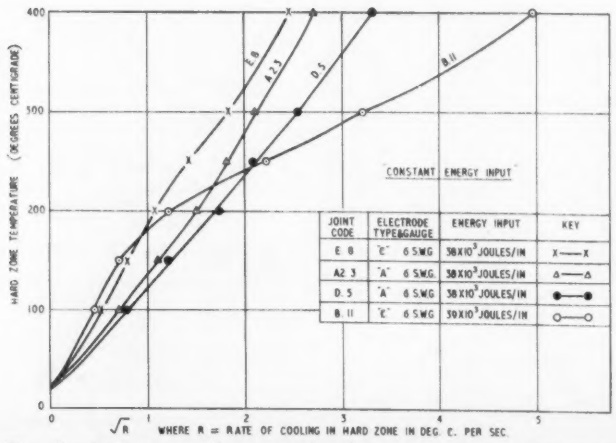
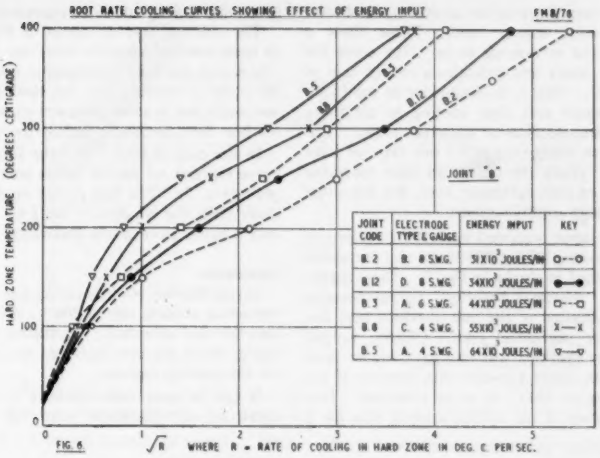

HARD ZONE TEMPERATURE (DEGREES CENTIGRADE)
400
300
200
100
0
E.8
A2.3
D.5
B.11
CONSTANT ENERGY INPUT
JOINT CODE | ELECTRODE TYPE&GAUGE | ENERGY INPUT | KEY
E 8 | "E" 6 S.W.G. | 38X10³ JOULES/IN
A2 3 | "A" 6 S.W.G. | 38X10³ JOULES/IN
D. 5 | "A" 6 S.W.G. | 38X10³ JOULES/IN
B. 11 | "C" 6 S.W.G. | 39X10³ JOULES/IN
0 1 2 3 4 5
√R
WHERE R = RATE OF COOLING IN HARD ZONE IN DEG. C. PER SEC.

Fig. 5.—Root rate cooling curves for the same energy input showing the effect of different joints.


ROOT RATE COOLING CURVES SHOWING EFFECT OF ENERGY INPUT
FM 8/76
HARD ZONE TEMPERATURE (DEGREES CENTIGRADE)
400
300
200
100
0
B.5
B.8
B.12
B.2
JOINT "B"
JOINT CODE | ELECTRODE TYPE & GAUGE | ENERGY INPUT | KEY
B.2 | B. 8 S.W.G. | 51X10³ JOULES/IN | o--o
B.12 | D. 8 S.W.G. | 34X10³ JOULES/IN | ●—●
B.3 | A. 6 S.W.G. | 44X10³ JOULES/IN | □--□
B.8 | C. 4 S.W.G. | 55X10³ JOULES/IN | X—X
B.5 | A. 4 S.W.G. | 64X10³ JOULES/IN | ▽—▽
0
1
2
3
4
5
√R WHERE R = RATE OF COOLING IN HARD ZONE IN DEG. C. PER SEC.
FIG. 6.

formation, i.e., the decomposition of retained austenite. This delayed transformation would be associated with the liberation of hydrogen and the consequent production of stress centres.

The 200–400 C. region is the temperature range in which the austenite to martensite transformation takes place in the majority of structural steels, including " Ducol W27." At this transformation there is a sudden decrease in the solubility of hydrogen in steel and hydrogen is forced out of solution leading to the possible production of stress centres in the martensite. The rate of cooling at 300 C. gives a good indication of the cooling rate during the transformation which may account for the best correlation between cooling rate and hard zone cracking occurring at 300 C. This cooling rate has also been taken as the basis of the thermal severity curves which are described later.

Fig. 1 shows a group of square root cooling rate curves for type " A " electrode. The different curves represent variations in energy input and type of joint. The curves shown in broken lines are for specimens which cracked, and the full line curves are for un-cracked specimens. The curves shown are typical of many which have been obtained for this particular electrode/steel combination, not only in the test structure but also in restrained weldability tests of the Reeve type and certain unrestrained weldability tests. It is seen that a cooling rate of about 6 C. per second at 300 C. is critical for this electrode, and cracking is likely to occur when this rate is exceeded.

A similar group of curves for electrode " B " is shown in Fig. 2. Here it will be noticed that the critical cooling rate is about two degrees C. per second higher than in the case of electrode " A." This increase in the critical cooling rate represents a definite advantage where the weldability of " W27 " steel is concerned. The main difference between electrodes " A " and " B " is that electrode " A " has a high titania content in the coating and produces a viscous slag, whereas the coating of electrode " B " contains basic materials in addition to titania and produces a fluid slag. It would be interesting to know why these different slags affect the weldability of " W27 " steel.

In the case of electrode " C " the slowest cooling rate recorded for cracked specimens was 10·2 C. per second, at 300 C. while one specimen showed no cracking where a cooling rate of 12·0 C. per second had been recorded. It may appear that the critical cooling rate of 11 C. per second for electrode " C " has been based on too few results, but, as in the case of electrodes " A " and " B," there is evidence from other tests to confirm this figure. Four root rate curves for this electrode are shown in Fig. 3.

The critical cooling rates derived for the three electrodes tested are compared in Fig. 4. It will be observed that there is a critical zone shown for each electrode, where hard zone cracks may or may not occur, and that these zones cover variations in cooling rates of 2 to 3 deg. C. p r second. The presence of these zones, instead of a sharp transition from cracking to no cracking, is due mainly to the fact that the steel used in this investigation was made up of a number of casts with variations in chemical composition. This critical zone is useful in that it serves as a guide to variations in weldability likely to be found in practice when using different casts of a steel to a certain nominal composition.

Derivation of Thermal Severity Curves

The square root cooling rate curves, which have been used to show the existence of critical cooling rates, vary in their form with variation in energy input* and joint geometry. An increase in energy input will increase the slope of the root rate curve as a whole, i.e., by lowering the rate of cooling at any given temperature. Joint geometry influences the shape of the root rate curve. Ideally, when the weld is made on a mass of metal which represents an infinite heat sink, the root rate curve should be a straight line according to Rosenthal[1]. In practice, this straight line relationship applies only until the background temperature of the heat sink begins to rise and the slope of the curve then changes to satisfy the new conditions. As the various metal sections adjacent to the joint become heated, the rate of heat conduction away from the weld must decrease, causing an increase in the slope of the root curve. At the lower temperatures air cooling becomes an important factor.

*The term energy input as used in this paper means the total arc energy. In practice, due to losses, about 80–90 per cent. of this energy is effective in heating the plates.

Fig. 5 shows a group of curves for several types of joint welded with the same energy input. These show a difference in form and in average slope. The curve for joint B crosses the others and indicates a slower rate of cooling below 200°C. This is no doubt due to the 1½ in. block becoming heated and then cooling in air more slowly than the thinner sections of the other joints. The effect of variations in energy input for one type of joint is shown in Fig. 6. Here the curves all have the same form, characteristic of that particular joint, but the slope increases as the energy input is raised.

When the energy input is plotted against the reciprocal of the square root cooling rate at 300°C. for any particular joint a curve is obtained as shown in Fig. 7. These curves have been termed "Thermal Severity" curves because their slope is an indication of the rate at which heat can flow away from the particular joint. Clearly, welded joints between heavy sections will require a higher level of energy input than joints between thin sections if the same rate of cooling at 300°C. is to be obtained. This fact becomes important if the critical cooling rate for a given electrode is not to be exceeded.

The thermal severity curves in Figs. 7–18 are shown as cross-hatched areas to cover the scatter of the results. The scatter has been explained in some cases as a result of the order of welding, i.e., the close proximity of previous test welds has in some instances provided additional paths for heat flow, causing a slightly more severe test.

In the case of joint "A," the four points lying on the curve marked A1 are for welds near a corner of the $\frac{3}{8}$ in. plate (Fig. 7). The two points marked A2 are for welds away from the corners of the $\frac{3}{8}$ in. plate, the joint, as a result, being more severe thermally.

Discussion

On the thermal severity curves just described (Figs. 7–18) the actual cooling rate at 300°C. is included on the "X" axis for easy reference. Equivalent fillet sizes for various energy levels are also provided as a more practical guide for the welding engineer.

It can be seen that reference to the thermal severity curve for any particular joint will show the minimum

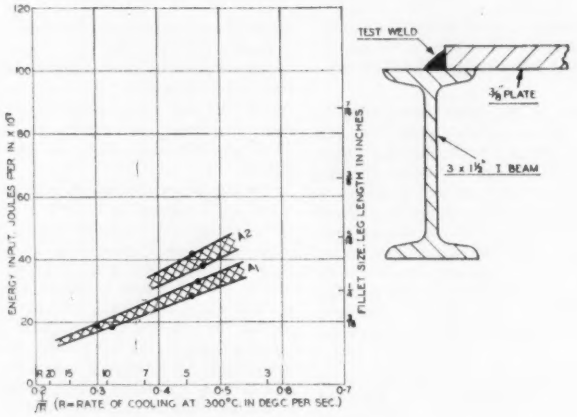

ENERGY INPUT, JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
A2
A1
R 20 15 10 7 5 3
(R=RATE OF COOLING AT 300°C. IN DEG.C. PER SEC.)
TEST WELD
3/8" PLATE
3 x 1½" T BEAM

Fig. 7.—Thermal severity of joint A.

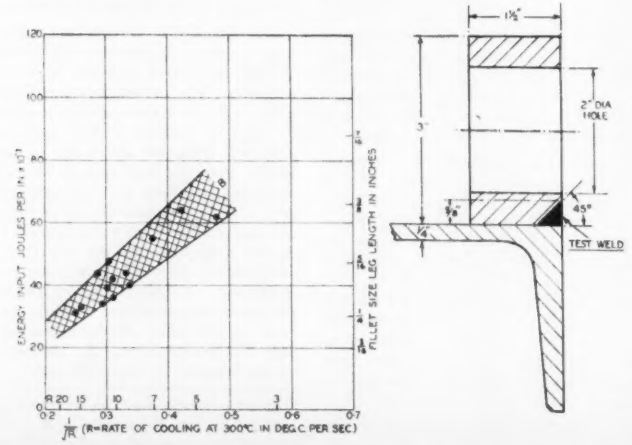

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
(R=RATE OF COOLING AT 300°C IN DEG.C. PER SEC)
1½"
2" DIA HOLE
3"
45°
TEST WELD

Fig. 8.—Thermal severity of joint B.

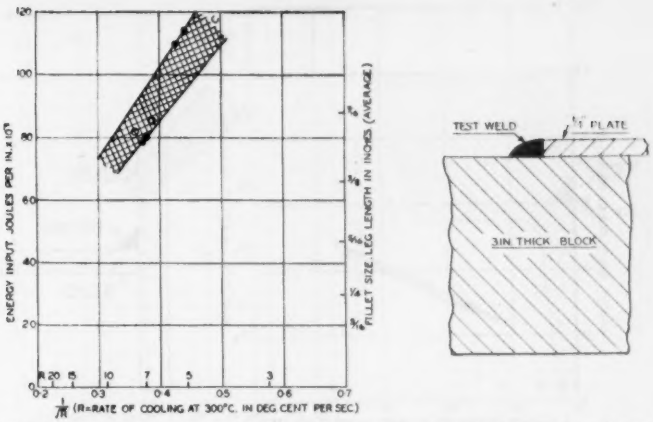

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES (AVERAGE)
R 20 15 10 7 5 3
1/√R (R=RATE OF COOLING AT 300°C. IN DEG CENT PER SEC)
TEST WELD
1" PLATE
3 IN. THICK BLOCK

Fig. 9.—Thermal severity of joint C. Note.—The open circles represent two similar welds made on a 6-in. thick block.

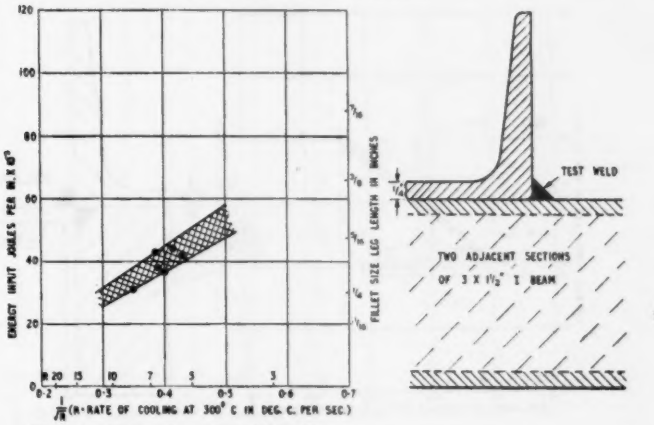

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
1/√R (R=RATE OF COOLING AT 300° C IN DEG. C. PER SEC.)
TEST WELD
TWO ADJACENT SECTIONS OF 3 X 1½" I BEAM

Fig. 10.—Thermal severity of joint D.

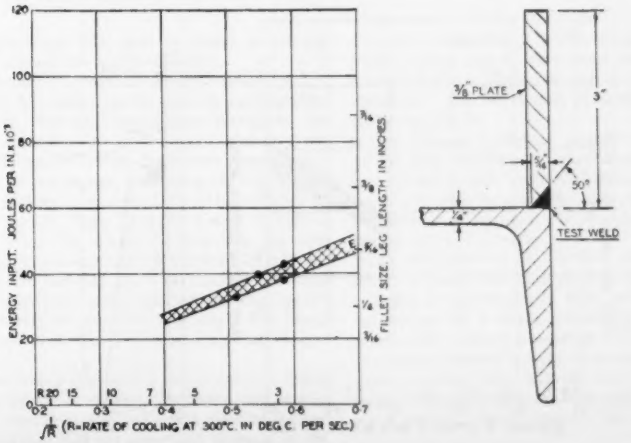

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
1/√R (R=RATE OF COOLING AT 300°C. IN DEG.C. PER SEC.)
3/8" PLATE
3"
50°
TEST WELD

Fig. 11.—Thermal severity of joint E.

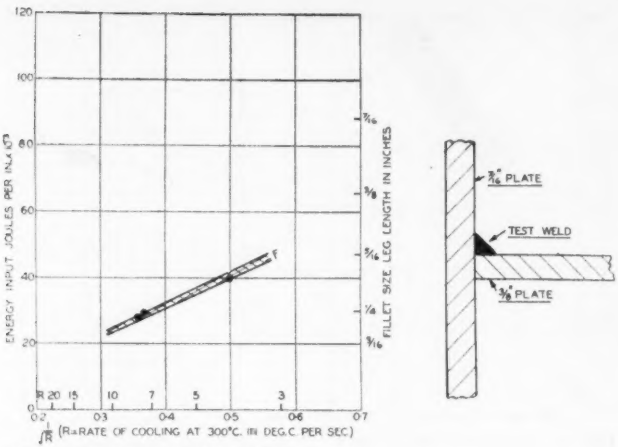

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
(R=RATE OF COOLING AT 300°C. IN DEG.C. PER SEC.)
F
13/16" PLATE
TEST WELD
3/8" PLATE

Fig. 12.—Thermal severity of joint F.

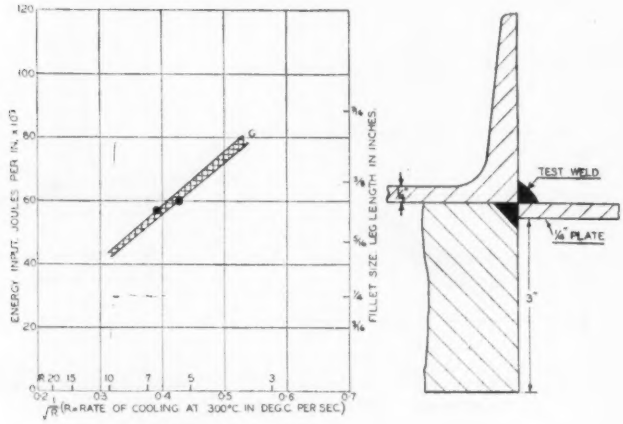

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
(R=RATE OF COOLING AT 300°C. IN DEG.C. PER SEC.)
G
TEST WELD
1/4" PLATE
3"

Fig. 13.—Thermal severity of joint G.

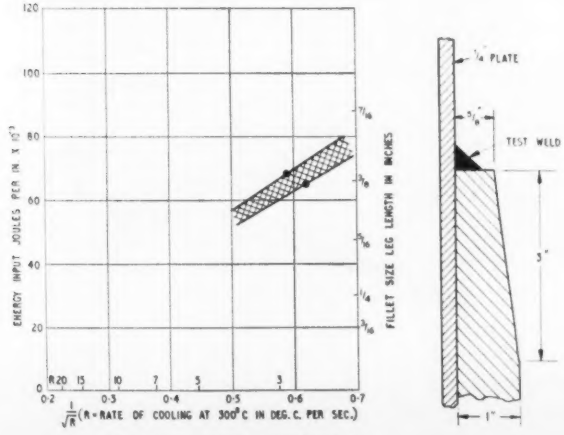

ENERGY INPUT JOULES PER IN. x 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
(R=RATE OF COOLING AT 300°C IN DEG. C. PER SEC.)
1/4" PLATE
5/16"
TEST WELD
3"
1"

Fig. 14. Thermal severity of Joint H.

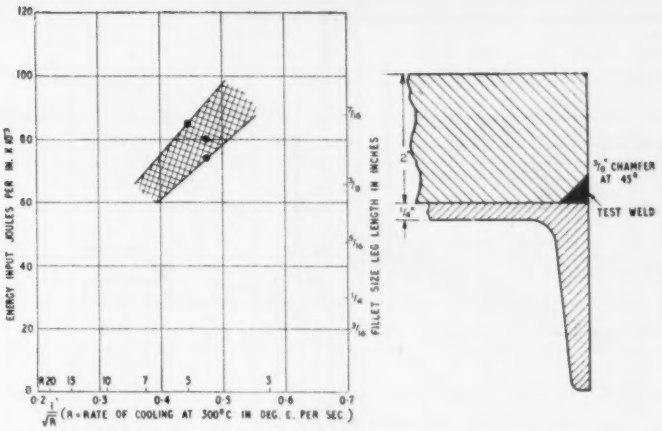

ENERGY INPUT JOULES PER IN. X 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
1/√R (R = RATE OF COOLING AT 300°C IN DEG. C. PER SEC.)
5/16" CHAMFER AT 45°
TEST WELD

Fig. 15.—Thermal severity of joint J.

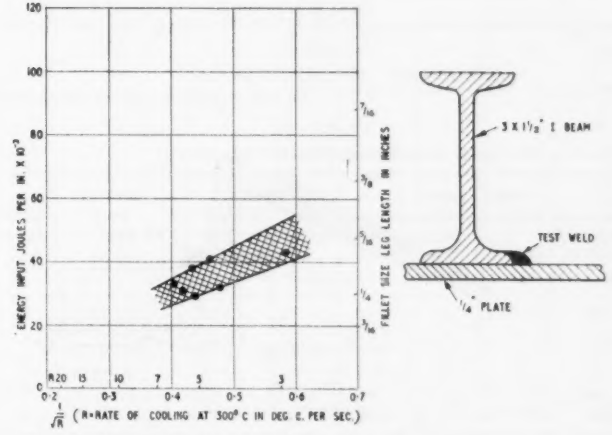

ENERGY INPUT JOULES PER IN. X 10³
FILLET SIZE LEG LENGTH IN INCHES
R 20 15 10 7 5 3
1/√R (R = RATE OF COOLING AT 300°C IN DEG. C. PER SEC.)
3 X 1½" I BEAM
TEST WELD
¼" PLATE

Fig. 16.—Thermal severity of joint K.

energy input (minimum fillet size) necessary to ensure that the critical cooling rate is not exceeded.

The determination of thermal severity curves for all types of joint to be welded would entail a considerable amount of work, but an approximate curve can be obtained from consideration of the joint geometry by comparison with similar joints for which results have been obtained. In this respect, it is interesting to compare joints A, E and F (Figs. 7, 11 and 12), B, G and J (Figs. 8, 13 and 15), D and H (Figs. 10 and 14) and K and L (Figs. 16 and 17). The critical cooling rate for any electrode/steel combination can be determined by a series of C.T.S. tests*. In this way, the most suitable electrode for welding any given steel may be selected, and satisfactory structural welds may be obtained by laying a fillet large enough to ensure that the critical cooling rate is not exceeded.

It is considered that a fillet weld between two 3-in. thick blocks will provide the most thermally severe joint attainable, with weld sizes up to ½ in. leg length, because further increases in thickness will not cause any increase in the rate of cooling at 300°C.

In this connection, it is interesting to note that, where tests on joint type C were made on a 6-in. thick block instead of a 3-in. block, the cooling rate at 300°C. was not increased. The two points obtained are shown as open circles on Fig. 9.

The slope of a thermal severity curve can be related to the total thickness of material adjacent to the weld, i.e., the size of path available for heat flow away from the weld, and also the extent of such material. In this way the severity of the joint can be related to an equivalent test in the C.T.S. series of tests. The C.T.S. tests are based on conditions of heat flow through various thicknesses of plate material adjacent to the test weld.

These considerations of joint geometry emphasise the inadequacy of a single weldability test as a basis for satisfactory welding procedure. Obviously a single test of average thermal severity is unnecessarily severe where joints between light sections are being considered, yet might lead to dangerous conclusions being drawn where joints between heavy sections are concerned. Either a

* See Appendix II.

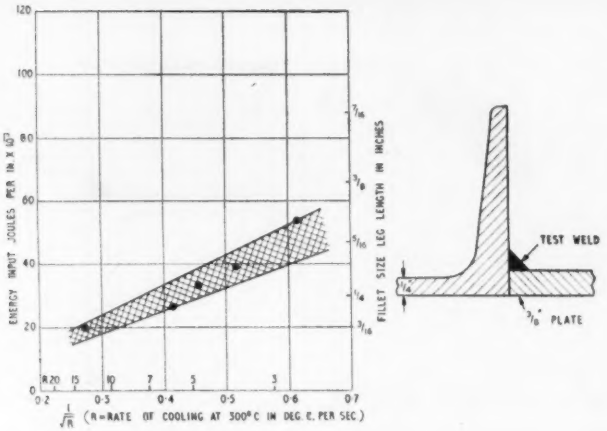

ENERGY INPUT JOULES PER IN X 10³
FILLET SIZE LEG LENGTH IN INCHES
TEST WELD
PLATE
R 20 15 10 7 5 3
1/√R (R=RATE OF COOLING AT 300°C IN DEG. C. PER SEC.)

Fig. 17.—Thermal severity of joint L.

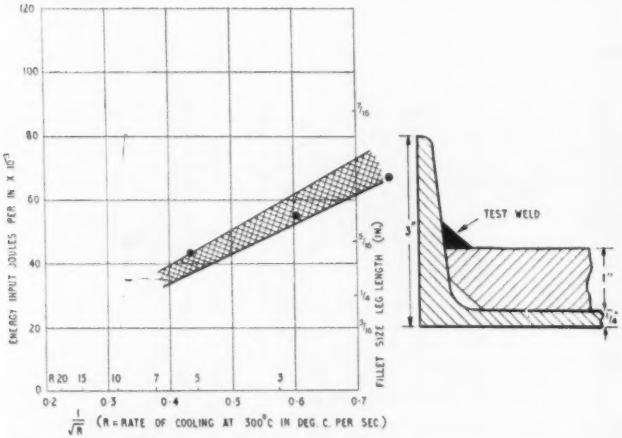


Fig. 18.—Thermal severity of joint M.

weldability test should be made which has a thermal severity similar to that of the joint, or the approximate severity of the joint should be estimated in terms of thermal severity curves and the welding procedure derived from considerations of the critical cooling rate of the electrode.

Conclusions

1. Cooling curves have been observed at a point in the hard zone of metal-arc welds on a number of different structural joints in Ducol W27 steel, and it has been shown that the rate of cooling at 300°C. can be used as a criterion for determining whether hard zone cracking will occur.

2. Critical rates of cooling (at 300°C.), above which hard zone cracking occurs, have been derived for Ducol W27 steel when welded with three different electrodes. The electrodes used were from B.E.A.M.A.-I.O.W. coating groups 2, 3 and 6 and these gave critical cooling rates at 300°C. of approximately 6, 8 and 11 deg. C. per second.

3. Thermal severity curves have been produced for a number of structural joints. These curves relate energy input and weld fillet size to the cooling rate at 300° C. in the hard zone. The slopes of the thermal severity curves indicate the relative severity of the joints.

Appendix I
TEST PROCEDURE

(a) Welding Conditions

The different types of joint were welded into a structure to provide a severe degree of restraint such as may exist in practice. The structure was welded using variations of both fillet size and electrode type.

The electrodes were stored in a warm cupboard and, immediately prior to welding, were baked in an oven at 110°C. for a minimum period of one hour. This was done to ensure that the moisture content would be at a minimum and more constant value. In order to obtain a uniform fillet size, each electrode was marked with a file at points along the length to be deposited. The welder

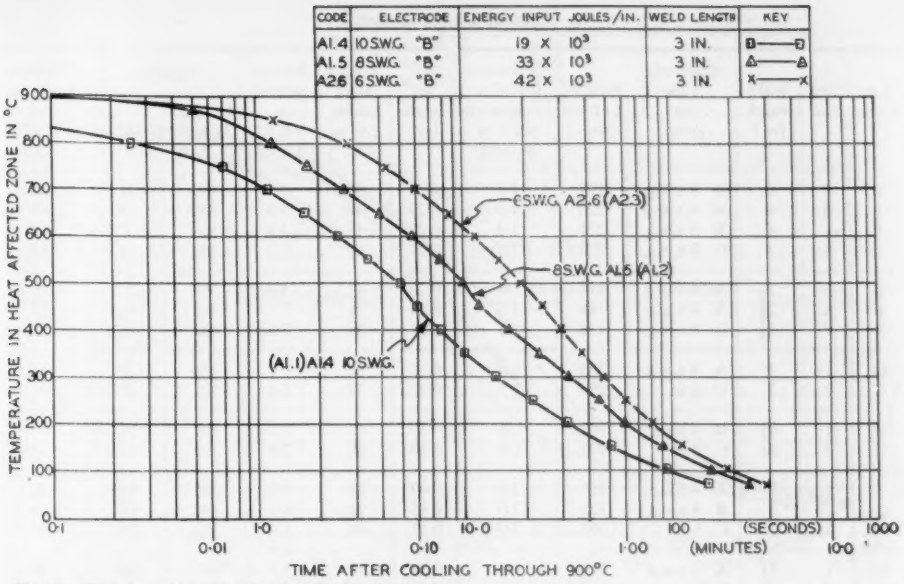

CODE
ELECTRODE
ENERGY INPUT JOULES/IN.
WELD LENGTH
KEY
A1.4 10 S.W.G. "B" 19 X 10³ 3 IN.
A1.5 8 S.W.G. "B" 33 X 10³ 3 IN.
A2.6 6 S.W.G. "B" 42 X 10³ 3 IN.
TEMPERATURE IN HEAT AFFECTED ZONE IN °C
6 S.W.G. A2.6 (A2.3)
8 S.W.G. A1.5 (A1.2)
(A1.1) A1.4 10 S.W.G.
(SECONDS)
(MINUTES)
TIME AFTER COOLING THROUGH 900°C

Fig. 19.—Direct cooling curves for joints A1 and A2.

TABLE III

SUMMARY OF EXPERIMENTAL RESULTS

Joint Code	Test No.	Weld length (in.)	Electrode Type and gauge	Welding Current (amp.)	Deposition Ratio (in. of electrode per 1 in. of weld)	Av. leg length (in.)	Energy input (joules per in. $\times 10^{-3}$)	Rate of cooling at 300°C. (°C./sec.)	Hardness		Cracking V+H leg / 2 (%)
									Av. peak H.A.Z. (V.P.N.)	Av. weld Metal (V.P.N.)	
A1	1	3	A 10 s.w.g.	132	1·5	0·17	19	10·8	403	245	3·17
A2	2	3	A 8 s.w.g.	179	1·6	0·22	29	4·8	355	232	ni
A1	3	3	A 6 s.w.g.	221	1·5	0·29	38	4·5	306	224	nil
A1	4	3	B 10 s.w.g.	131	1·5	0·20	19	9·5	398	233	nil
A1	5	3	B 8 s.w.g.	175	1·5	0·27	33	4·7	336	211	ni
A2	6	3	B 6 s.w.g.	221	1·5	0·27	42	4·8	307	187	nil
B	1	5	A 8 s.w.g.	176	1·5	0·29	33	14·7	407	299	15·6
B	2	5	B 8 s.w.g.	180	1·5	0·25	31	16·0	401	222	25·6
B	3	5	A 6 s.w.g.	220	1·5	0·31	44	9·0	391	225	19·5
B	4	5	B 6 s.w.g.	222	1·5	0·29	45	12·2	394	222	9·4
B	5	5	A 4 s.w.g.	320	1·5	0·38	64	5·6	332	208	nil
B	7	5	C 6 s.w.g.	206	1·5	0·32	48	12·0	378	256	nil
B	8	5	C ¼ in.	281	1·5	0·36	55	7·1	344	217	nil
B	9	5	A 6 s.w.g.	220	1·5	0·27	42	10·2	384	220	23·0
B	10	5	B 6 s.w.g.	221	1·5	0·28	40	8·8	394	213	15·2
B	11	5	C 6 s.w.g.	202	1·5	0·29	39	11·0	379	231	nil
B	13	5	C 8 s.w.g.	163	1·5	0·26	36	10·2	398	265	1·9
C	1	5	A 4 s.w.g.	307	2·0	0·40	79	7·0	377	207	1·6
C	2	5	C ¼ in.	300	2·0	0·43	80	7·1	348	236	nil
C	3	5	A 4 s.w.g.	295	3·0	0·45	110	5·5	309	192	nil
C	4	5	C ¼ in.	270	3·0	0·44	114	5·2	334	233	nil
D	1	3	A 6 s.w.g.	218	1·5	0·22	37	6·0	392	218	nil
D	2	3	B 6 s.w.g.	209	1·5	0·29	42	5·4	403	210	nil
D	3	3	C 6 s.w.g.	198	1·5	0·29	44	6·0	385	250	nil
D	4	3	A 8 s.w.g.	180	1·5	0·22	31	8·3	418	244	3·5
D	5	3	A 6 s.w.g.	220	1·5	0·28	38	6·6	405	230	4·1
D	6	3	C 6 s.w.g.	205	1·5	0·29	43	6·7	384	249	nil

TABLE III (Continued)

Joint Code	Test No.	Weld length (in.)	Electrode Type and gauge	Welding Current (amp.)	Deposition Ratio (in. of electrode per 1 in. of weld)	Av. leg length (in.)	Energy input (joules per in. $\times 10^{-3}$)	Rate of cooling at 300°C. (°C./sec.)	Hardness		Cracking V+H leg / 2 (%)
									Av. peak H.A.Z. (V.P.N.)	Av. weld Metal (V.P.N.)	
E	3	4	A 8 s.w.g.	177	1·5	0·27	33	3·8	397	212	nil
E	4	4	A 6 s.w.g.	220	1·5	0·27	40	3·3	342	197	nil
E	7	4	B 6 s.w.g.	221	1·5	0·27	43	2·9	365	202	nil
E	8	4	C 6 s.w.g.	220	1·5	0·27	38	2·9	339	220	nil
F	5	2½	A 6 s.w.g.	214	1·5	0·28	40	4·0	369	215	nil
F	6	2½	A 8 s.w.g.	188	1·5	0·24	28	7·7	361	212	nil
F	7	2½	C 8 s.w.g.	172	1·5	0·21	29	7·4	402	252	nil
G	1	3	A 4 s.w.g.	295	1·5	0·36	60	5·5	358	215	nil
G	2	3	C ¼ in.	290	1·5	0·35	57	6·6	371	227	nil
H	1	4½	B 4 s.w.g.	302	1·6	0·37	65	2·7	307	181	nil
H	2	4½	C ¼ in.	275	1·6	0·39	68	2·6	295	213	nil
J	1	7	A 4 s.w.g.	317	2·0	0·49	85	5·2	305	210	nil
J	2	7	B 4 s.w.g.	321	2·0	0·45	74	4·4	342	185	nil
J	3	7	C ¼ in.	302	2·0	0·43	80	4·4	302	216	nil
K	1	5½	A 6 s.w.g.	213	1·5	0·24	38	5·7	347	209	9·1*
K	2	5½	B 6 s.w.g.	215	1·5	0·27	41	5·1	371	212	1·6*
K	3	5½	C 6 s.w.g.	200	1·5	0·28	43	2·9	307	226	nil
K	4	5½	A 8 s.w.g.	176	1·5	0·24	33	5·7	397	248	4·2
K	5	4	A 8 s.w.g.	178	1·5	0·22	29	5·3	395	218	3·5
K	6	4	B 8 s.w.g.	176	1·5	0·21	31	5·7	373	202	nil
K	7	4	C 8 s.w.g.	160	1·5	0·20	32	4·4	365	226	nil
L	1	6	A 8 s.w.g.	177	1·5	0·24	26	6·5	376	206	30·3
L	2	5½	A 6 s.w.g.	220	1·4	0·30	39	4·3	400	215	8·7
L	3	5½	A 10 s.w.g.	131	1·5	0·18	20	13·5	412	250	6·7
L	4	12	A 4 s.w.g.	290	1·3	0·34	54	2·6	303	192	nil
L	5	12	A 6 s.w.g.	220	1·3	0·23	33	4·8	386	221	nil
M	1	7½	A 4 s.w.g.	302	1·5	0·35	55	2·8	325	204	nil
M	3	7½	C ¼ in.	275	1·6	0·38	67	1·9	302	216	nil
M	4	7½	A 6 s.w.g.	220	1·6	0·29	43	5·2	395	205	1·6

* Cracking occurred in the end section adjacent to a channel flange which caused a faster cooling rate than indicated at the weld mid position, this is confirmed by higher hardness readings in the end section hard zone.

then made each weld so that the file marks on the electrode coincided with chalk marks on the test assembly.

All the welds were made by the metal arc process using alternating current. The current was measured on a moving iron ammeter working from a 500/5 current transformer. Voltage measurements were taken with a rectifier moving coil instrument. The energy input to the welds was measured with an induction type integrating watt hour meter.

The whole test assembly was allowed to cool to room temperature before making each test weld.

(b) Determination of Cooling Rates

Temperatures in the heat-affected zone of each weld were measured by means of a chromel-alumel thermo-couple. Couple wires (22 B. and S.G.) were fused together to form the hot junction. This was flash welded into a small steel thimble which was then inserted in a $\frac{5}{32}$ in. reamed hole, a section through a thermo-couple in weld type C being shown in Fig. 22. The hole was positioned half way ($\frac{1}{2}$ of the way for joint B) along the length of the proposed run with its centre $\frac{5}{32}$ in. from the weld root. The ends of the thimbles were varied in thickness so that the couple would be a greater distance below the plate surface where a larger gauge electrode was to be used. The distances used were 50, 55, 60 and 70 thousandths of an inch for 10, 8, 6 and 4 s.w.g. electrodes. This position lay just inside the heat affected zone after welding.

The thermo-couple wires were connected via a cold junction to a fast response (0·3 seconds) millivoltmeter calibrated to read in degrees centigrade. The millivolt meter, together with a stop watch and voltmeter, was continuously photographed on 16 mm. film during and after welding until the recorded temperature had dropped to 50°C. For this purpose a R.A.F. gun camera was used which had been modified to work at a rate of two exposures per second, a typical film recording being shown in Fig. 23. The voltmeter was connected across the weld arc and was used only to relate the start and duration of a weld to the cooling cycle. The temperature indicator

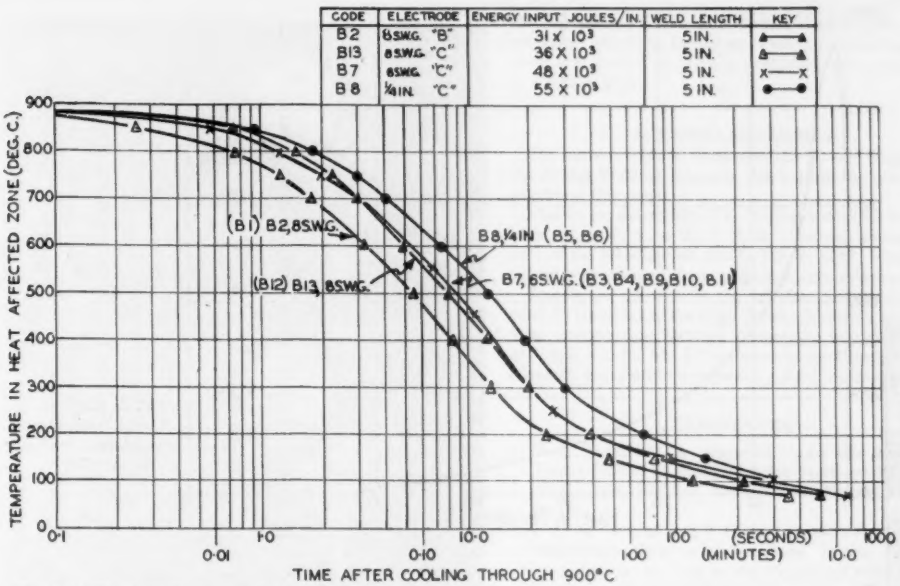


Fig. 20.—Direct cooling curves for joint B.

and stop watch had black dials with white markings, which appear on the film negative as white dials and black markings, thus reducing reflections and making film reading much easier.

The films were read using a film strip projector fitted with a 25 mm. microscope lens, and direct cooling curves were plotted on linear graph paper from the results. Rates of cooling at various temperatures were obtained by taking tangents from the direct cooling curves with a perspex ruler along which a centre line had been scribed.

Cooling curves plotted on logarithmic paper for two of the joints*, are shown in Figs. 19 and 20. A typical direct rate cooling curve from which tangents were taken is given in Fig. 21.

(*c*) *Examination of Test Welds*

The test welds were cut out of the assembly with a mechanical saw. Three sections were then cut by hand hacksaw from each weld at approximately $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of its length from the start. These sections were ground flat and micro-polished on one face normal to the length of the weld. The specimens were then etched in a solution of three per cent. picral containing three per cent. hydrochloric acid, and examined microscopically at a magnification of 400 diameters for cracks both in the weld metal and in the heat affected zone of the plate. Where cracks were found their lengths were measured directly on the screen of a projection microscope at a magnification of 250 diameters. A hard zone crack in joint B is shown in photomicrograph Fig. 24. Fillet sizes also were measured with the projection microscope adjusted to give a magnification of 5 diameters.

All crack lengths were expressed as a percentage of the length of the leg in which they occurred.

Hardness explorations were made on the centre section of each test weld using the " Vickers Diamond Pyramid " indenter with a load of 10 Kg. Indentations were made on a line perpendicular to the fusion line, from the weld metal through the heat affected zone to the unaffected plate. From the results of these readings the position of maximum hardness in the heat affected zone relative to the fusion line was found. Further indentations were then made parallel to the fusion line in the region of maximum hardness, and the average of these results is reported as " average peak hardness " in the heat affected zone.

Appendix II

C.T.S. WELDABILITY TEST

The C.T.S. weldability test and results obtained with it will be fully described in a future report and it has been mentioned here, only in order to indicate how a weldability test can be selected to suit the thermal characteristics of any given joint.

A photograph of the range of C.T.S. tests is given in Fig. 25, each test assembly consisting of two plates of equal thickness ($\frac{1}{4}$, $\frac{1}{2}$, 1 and 2 ins.) giving a range of four test assemblies. The top plate size is 3 in. square and the bottom plate 4 ins. by 7 ins. The top plate is securely bolted to the bottom plate and anchor welds are made along the two opposite sides of the top plate in the direction of the major axis of the bottom plate. Two test welds are made as fillet welds between top and bottom plates on each assembly, the first weld being made where the bottom plate extends only slightly beyond the top plate and the second where there is a considerable extension of the bottom plate. The first test weld gives heat flow through two plate sections (bithermal flow) and the second weld gives heat flow through three plate sections (trithermal flow) and therefore, two different degrees of thermal severity are obtained with each plate thickness. The plate thickness of the series of tests has been selected so that a total of eight different severities will be obtained with no duplication. Each of these severity grades will give a

*A full set of cooling curves is available on loan from the British Welding Research Association, 29, Park Crescent, London, W.1.

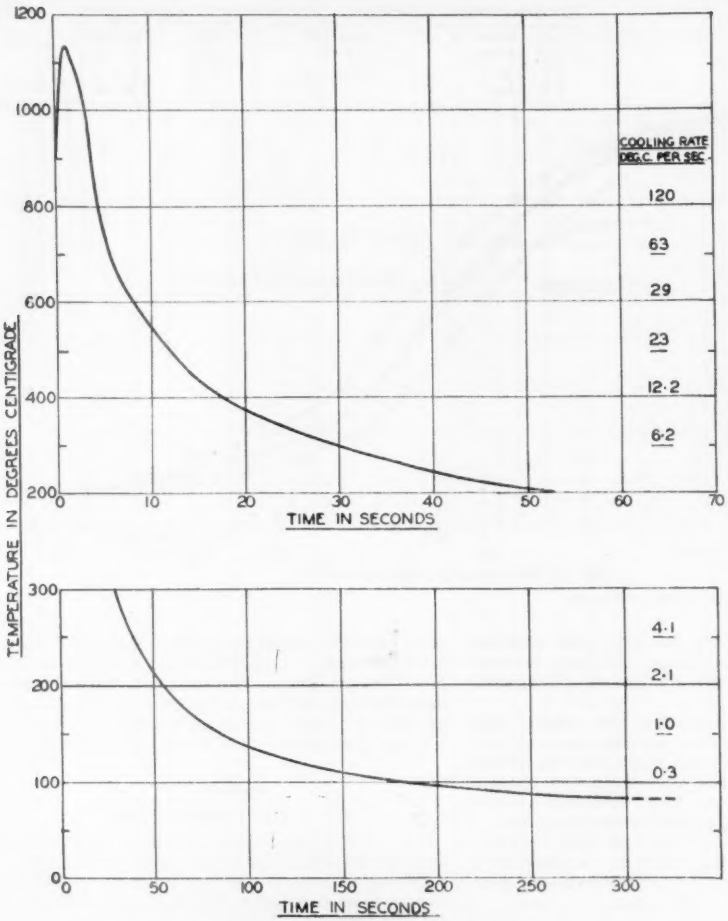


Fig. 21 (Left).— Direct cooling curve as plotted from the film negative.

Fig. 22. (Left).— Thermocouple in joint C (mag. × 5).

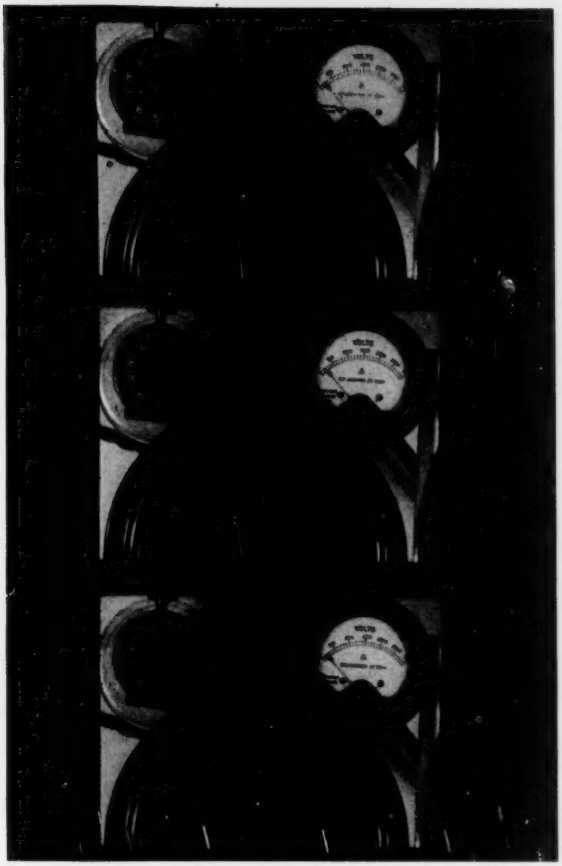


Fig. 23.—Film recording.

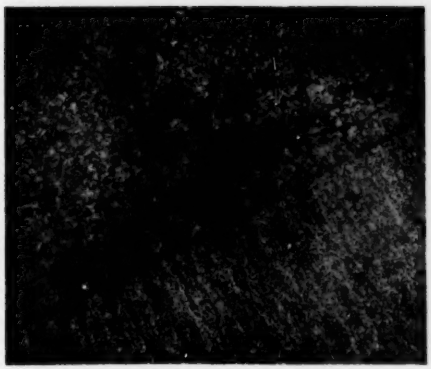


Fig. 24.—Hard zone crack in joint B (mag. × 50).

thermal severity curve of a certain slope which can be compared with those for the set of joints given in Figs. 7–18 when it is desired to select a weldability test comparable to a certain joint.

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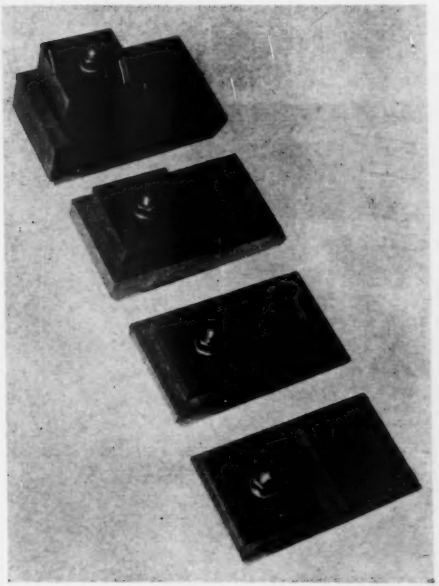

Fig. 25.—View of C.T.S. tests.

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